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TANK GUN BARREL RESHAPING—CONCEPT TO IMPLEMENTATION

JAMES GARNER, DR. MARK BUNDY, ALBERT POMEY, AND WALTER N. ROY

The U.S. Army Research Laboratory has discovered a process that will allow tank gun barrels to be produced with tighter tolerance in their centerline contour. Improved centerline uniformity translates into improved shooting consistency from barrel to barrel. This article describes the approach taken and the lessons learned, from searching for and acquiring a program sponsor, through planning and execution of hardware development, test validation, and preparation for transition to implementation.

The U.S. Army always seeks to improve the performance of its tactical systems. The methods by which these performance improvements are initiated, quantified, validated, approved, and implemented are sometimes long-lived and torturous. The following gives a view from the bench level as to how these processes unfolded and the lessons learned along the way.

Ballisticians have long suspected that a gun's centerline contour has a significant affect on its accuracy. Hence, the ability to control the centerline has been an essential requirement in the system specifications of the Abrams tank series. However, imposing and achieving tighter tolerances on the centerline would have been impossible without the recent discovery of a method to precisely control a gun tube's centerline shape. Although characterizing and perfecting the means of application was the focus of the barrel reshaping program, technical details are omitted here in favor of documenting the programmatic and acquisition-centered problems and lessons learned in starting and managing this effort.

The greatest beneficiaries of reshaping will be the poor-shooting or *rogue* tanks that have accuracy problems. The Fleet-zero approach currently used applies a computer correction factor to be used in firing and is based on the results of thousands of previous tank firings. Fleet-zero preempts individually characterizing each tank barrel through firings, which is prohibitively expensive from a time and cost perspective. The problem is that while the correction factors are based on the average, some of the tanks may be far from average and therefore suffer accuracy shortcomings. The reshaping effort creates a barrel centerline that is the fleet average (within reshaping tolerances) and minimizes accuracy deviations due to centerline differences.

FUNDING THE PROCESS

Every researcher knows that many good ideas remain unexploited for lack of funding; somewhere, somehow, money must be made available to carry the idea from concept through development and validation to the implementation stage. This is particularly problematic when the scientific discovery, such as barrel reshaping, does not occur under the auspices of a larger, overriding program with a well-defined funding line.

As described above, the primary benefit from barrel reshaping is improved accuracy for the fleet-average barrel. Figure 1 outlines a significant events calendar, with time zero marking the onset of the fully funded, well-defined barrel reshaping initiative (BRI). Scientists at the U.S. Army Research Laboratory's (ARL's) Weapons and Materials Research Directorate (WMRD) demonstrated that a barrel could be precisely shaped approximately three years prior to the time line origin. In the terminology of technology readiness level (TRL), it was a TRL three or fourth event. This characterization is that the technology is slightly beyond a proof of concept, but not all the technical details are known. Demonstrating that barrel reshaping can positively affect the mean projectile impact point occurred a year later. Figure 2 shows the benefit of reshaping for barrel serial number (SN) 4233 against a tank silhouette at a selected range.

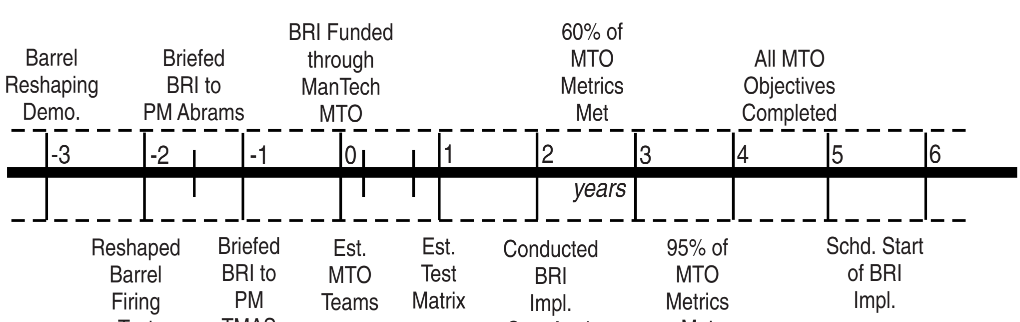

FIGURE 1. BARREL RESHAPING INITIATIVE TIME LINE OF EVENTS

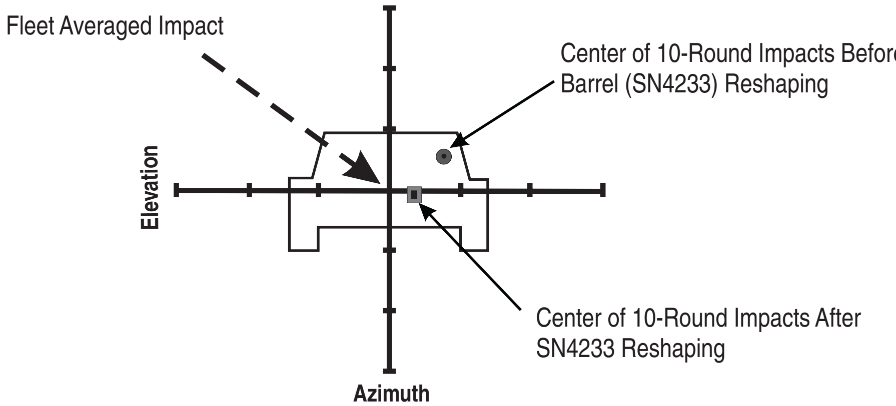

FIGURE 2. INITIAL PERFORMANCE IMPROVEMENT EXAMPLE

If, as noted, there was no existing umbrella program, then it might be asked who incurred the concept-demonstration costs of the first two years. The answer to that question is many-sided. First, in practice, there is latitude given to researchers at the *bench level* to explore fresh ideas and innovative techniques that may lead to new program start-ups. The WMRD Director's Research Initiative Program is such an example.

Second, in a case where funding would normally be an explicit requirement (such as range testing), an economical solution is to piggyback one investigation onto another, provided there is no added risk or cost. This was the method used to acquire the firing data of Figure 2, where the BRI proof of principle benefited from the ranges and the cooperation of the Army Test Center (ATC), co-located with WMRD at the Aberdeen Proving Ground.

And last, it is not unheard of for managers outside the immediate chain of the researcher's command, or even outside the researcher's agency, to invest *seed money* in promising new ideas on the chance that their organization may eventually gain from it. This later option was also used to offset the BRI concept demonstration costs, again benefiting from ATC's start-up investment in BRI. (Note, ATC eventually did reap a 10-fold return in benefits from BRI, in that they acquired the use of new centerline measurement equipment purchased in the BRI program and were paid to do all the BRI live-fire validation testing once the program became fully funded.)

Even with the potential performance benefits of Figure 2 clearly evident, it took two additional years to find a funding source for the full-scale BRI program. This emphasizes the difficulty of securing developmental dollars for a project that is outside the research and development pipeline of an overarching program.

During the decade prior to the barrel reshaping breakthrough, WMRD had a line-item budgeted program called *enhanced tank gun accuracy*; however, it transitioned into a *smart munitions* program prior to the start of the events in Figure 1. Thus, BRI was an independent idea looking for a financial backer at the level of ~\$1–2 million per year, for 3–5 years, to bring the technology from concept demonstration to the point of wide-scale implementation.

The original program solicitation was built around the reshaping method and preliminary firing results of Figure 2, complemented with the benefits to be gained under the Training and Doctrine Command's (TRADOC's) Fleet-Zero policy. Recognizing the importance of the technology breakthrough, WMRD's Director enlisted the joint support and participation of the U.S. Army Benet Laboratory, co-located with Watervliet Arsenal (where tank gun barrels are manufactured), and the recognized experts in barrel manufacturing technology. Next, with the combined endorsement of both WMRD and Benet Laboratory Directors, the BRI proposal was briefed to the overall gun system manager (at the time)—the project manager's office for Abrams tank (PM Abrams, now incorporated into PM Combat Systems). This event is marked at approximately *-1.5 years* on the timeline of Figure 1.

Although PM Abrams thought the initial results were promising and pledged support in the "out years," their existing budget commitments prevented them from serving as the program patron in the near term.

Although PM Abrams thought the initial results were promising and pledged support in the *out years*, their existing budget commitments prevented them from serving as the program patron in the near term. A second organization, known to have previously sponsored improvements to barrel-related subsystems, was the program management office of Tank Main Armament Systems (PM TMAS, now incorporated into PM Maneuver Ammunition Systems, PM MAS). Acknowledging the potential benefits of barrel reshaping, but also unable to solely and immediately underwrite the project costs, PM TMAS briefed the BRI proposal up their chain of command—without success, however. These failed attempts to fund the BRI took two years to explore, but fortunately, the search had generated attention and brought awareness to a wide group of individuals, one of whom made a pivotal suggestion—why not propose BRI to the Army Materiel Command's Manufacturing Technology (AMC ManTech) program.

Following this suggestion, the coordinator for existing ARL ManTech projects was contacted, and a BRI ManTech proposal drafted and submitted. In accordance with ManTech proposal requirements at the time, it was necessary to identify a proposal cosponsor from within the Army who would invest at least of 25 percent of the total program cost. Although PM TMAS had not been able to fund the entire request, they were able and willing to serve as 25 percent cosponsor, should the ManTech proposal win approval.

Having met the minimum ManTech requirements, several additional steps were initiated that were helpful, if not decisive, in the proposal evaluation and ranking process. First, in addition to obtaining the signatures of PM TMAS as a financial coinvestor, and the endorsement of PM Abrams, as well as both ARL and Benet Laboratory Directors, a key decision was made to enlist the endorsement of BRI from the armor soldier's most direct spokesperson—the TRADOC Systems Manager (TSM) for the Abrams tank.

Second, a TSM Abrams representative was enlisted to accompany the BRI proposal team on several one-on-one briefings with individual members of the ManTech review board prior to their final selection meeting. This petitioning and constituency-building from the combined voice of both the technical and the user community was believed to be critical not only in gaining approval, but also in attaining a high program ranking (which helped ensure that if there were unexpected ManTech budget cutbacks, BRI would remain funded). These events brought the program to time zero on the scale of Figure 1.

Tasks	1st Year	2nd Year	3rd Year	4th Year
✦ Establish MTO teams. Begin accuracy testing a control set of gun tubes. Fabricate 1st generation reshaping machine and formulate prediction algorithm. Investigate relevant measurement methodologies. Initiate studies to optimize the reshaping process.	■			
✦ Begin reshape and accuracy testing of control tubes. Stress test sampling of reshaped tubes. Begin construction of 2nd generation machine. Down-select measurement technique. Fix technical requirements for development of fully automated machine.		■		
✦ Continue reshaping control tubes with 2nd generation machine, followed by accuracy testing. Investigate reshaping tolerance on accuracy. Begin contracting for 3rd, and final, machine design construction. Establish transportation unit requirements.			■	
✦ Complete accuracy testing of reshaping tubes and quantify average improvement. Construct transportation unit. Develop computer-based machine control between measurement and reshaping machines. Demonstrate and document operation of machines.				■

FIGURE 3.
INITIAL TIMETABLE FOR BARREL RESHAPING INITIATIVE OBJECTIVES

FIGURE 4.
MANUFACTURING TECHNICAL OBJECTIVE TEAM STRUCTURE

TEAM TASKING

The objectives and milestones of the ManTech-funded BRI manufacturing technical objective (MTO) were set out in the approved proposal, as displayed in Figure 3, but the team structure was not quantified until funding was secured. The division of tasks was guided by the process and goals of the program, as laid out in Figure 4. Specifically, since the tank barrel is exposed to high pressures, a *safety certification* team was commissioned to ensure that any changes made to the barrel would not affect the safety of the barrel or shorten its service life. A *fire and evaluation* team was created to quantitatively describe the accuracy improvements of the process. A *machine design* team was initiated to build machines to process the barrels both in the field and in production.

An *algorithm team* was initiated to predict where and to what degree the reshaping process was needed in order to transform a given barrel centerline to the preferred shape. A *transportation team* was assembled to identify and configure the conveyance vehicle for the field unit reshaping machine. Measuring the initial barrel centerlines is the starting point for the process, so a *measurements team* was formed to optimize that process. Finally, a *business team* was formed and tasked with the job of promoting the program and assuring continued compliance with user needs.

In addition to the seven teams, there was a management group, consisting of an overall MTO manager, an assistant manager, and an inter-team facilitator, as well as a laboratory-connected support group for assisting with program budgeting, fund transfers, and purchase requests. The objectives of each team and the duties of the administrators were formally described in a BRI management plan that was distributed to all team leaders.

Team members were selected from both inside and outside of the ARL, based upon who was most capable of contributing to the team objectives. For instance, the safety certification team was located at Benet Laboratory, where gun barrel stress and fatigue analysis is routinely conducted. The fire and evaluation team was managed from within the Army Test Center (ATC), recognized experts in conducting large-scale weapon accuracy tests. The machine design team was led from within ARL, but had team members from Watervliet Arsenal and Benet Laboratory. The business team was managed either by a representative from PM TMAS, the co-sponsor, or TSM Abrams. Program funds to cover the cost of labor and testing materials were transferred to the parent branch or organization of the team members.

The objective of the business team was to direct the course of action in areas relevant to transitioning the technology into practice.

The idea of a business team may seem superfluous to a technically related MTO and, therefore, deserving of a more detailed explanation. The objective of the business team was to direct the course of action in areas relevant to transitioning the technology into practice. Even though all the major weapon system managers and the user endorsed the MTO, there would invariably be new managers and new performance and financial priorities at the end of the four-year BRI MTO. Implementation questions would again be asked: Why should we do this? What is it going to cost? Is it worth the cost? The goal of the business team was to anticipate such questions and have answers at the ready. For instance, the business team first deliberated whether the emphasis of the test and evaluation team should be placed on promoting the worst-to-best gain in accuracy performance, or whether success should be sold on the fleet average performance improvement. Also debated was how the performance data should be presented—in the form of hit probability increase, potential round savings, or combat loss exchange ratio improvement. Furthermore, who should be involved in such comparison studies, and how often should the intermediate results be briefed?

PROGRESS REVIEWS

Each team met with the MTO manager two to three times per year to discuss progress, findings, or perhaps redirection of the specific goals that had been agreed upon at the beginning of the year. Notes from each meeting were recorded and circulated to all team members. When important results were obtained, such as meeting an MTO milestone the news was forwarded to ManTech and laboratory supervisors. At year's end, there was an all-team annual review, where every team made a formal presentation of their accomplishments. These annual reviews were held at various geographic sites such as West Point, NY, Aberdeen Proving Ground, MD, and PM Abrams Headquarters, Warren, MI to help disseminate program objectives to a wide spectrum of potentially affected groups.

Taking to task the search for answers to open questions ultimately strengthened subsequent presentations and prepared BRI for the final challenge—securing implementation funds.

In addition to the *self-imposed* internal MTO reviews described above, there were numerous (some mandatory) progress reports and informational briefings given to ManTech review panels, laboratory management at both ARL and Benet, the PM offices, Watervliet Arsenal, TSM Abrams, and special armor groups, such as the Army's Tank Gun Accuracy Committee, and the Marine Corps' Tank Officers Advisory Group.

In the category of *best program practices*, the external progress reports noted above were more than a one-way exchange of information; they provided valuable feedback to the MTO manager and business team on what questions were still left unanswered or unaddressed in the list of tasks highlighted in Figure 3. Taking to task the search for answers to open questions ultimately strengthened subsequent presentations and prepared BRI for the final challenge—securing implementation funds.

HARDWARE DEVELOPMENT AND TESTING STRATEGY

The overall four-year MTO Gantt chart was structured to investigate parallel hardware exploration and development in high-risk, high pay-off areas, such as improved speed and precision in the centerline measurement process. Down-selection to the most promising design track was scheduled for the second year, along with fixing critical design specifications for either sole-source purchases or open-bid requests for proposals (RFPs).

With regard to MTO contracts and purchases associated with hardware development, it was extremely important, from an expediency perspective, that the laboratory management authorized discretionary control and direction of MTO funds to the BRI program manager. Equally important was the rapid execution of purchase requests; typically the sequence of events from request (by team leaders) to approval (by MTO manager) to confirmation of available funds and submission of purchase order (by budget specialists) took only two days. Had laboratory supervisors asked for justification for each of the hundreds of items ordered, it would, in all likelihood, have protracted the program another year. These *best procurement practices* were a key to meeting the BRI timetable of Figure 3.

As indicated earlier, decisions on testing strategy were made in the first year to provide time for gun barrel (centerline) selection as well as time to request and receive delivery of the requisite ammunition. However, this statement alone may not convey the level of importance placed on validation testing for the purpose of unequivocally proving that the benefits of barrel reshaping are worthy of implementation. There was no doubt that barrel reshaping affects accuracy, as evidenced in Figure 2. The concern was that if the size of the test (number of barrels, number of occasions, and number of rounds per occasion) was not large enough, other confounding factors, such as round-to-round and occasion-to-occasion errors, would bring the level of confidence in the demonstrated improvement below the desired statistical degree of certainty.

As insurance, a comprehensive statistical analysis was conducted during the first-year...to determine the size of the test needed to provide a confidence level of at least 80 percent in the certainty of the testing results.

As insurance, a comprehensive statistical analysis was conducted during the first year (marked on the timeline of Figure 1) to determine the size of the test needed to provide a confidence level of at least 80 percent in the certainty of the testing results. To accomplish this, nearly one in every five program dollars (20 percent) went into testing, in what is believed to be the single largest accuracy test ever conducted on a tank-caliber main gun.

In hindsight, there was wisdom acquired with regard to test planning. A review and report of the intermediate firing results was promised and delivered to the program sponsors when the testing was 25 percent complete. However, no forethought or attention was paid to selecting a balanced mix of *poor and good shooters* in the first test group. As chance would have it, the first group was composed of fairly uniform centerlines (relative to the overall group). Consequently, they shot fairly consistently, even before reshaping. Not surprisingly, after further tightening the centerline consistency with the reshaping process, there was only a small accuracy improvement.

As a result, the initial BRI results did not leave a good first impression, diminishing early interest in BRI. This made it more difficult to promote its success when all barrels' shapes were taken into account and the average improvement was shown to be substantial. The lesson learned: plan, to the extent possible, to acquire and publicize intermediate test results that are indicative of the final performance norm.

GAUGING SUCCESS

There were five metrics posted in the original proposal for measuring the final success of the MTO program. Without specifically quantifying these metrics, they were, in general form:

1. Demonstrate a (stipulated percentage point) reduction in the after vs. before center-of-shot impact.

2. Improve the first-round probability of hit (PH) for reshaped barrels (by a stipulated number of PH-points, over a stipulated range of interest).

3. Acquire a 20-fold reduction in the manufacturing tolerance for barrel straightness.

4. Obtain a 6-fold reduction in barrel straightness measurement time.

5. Achieve a 2-fold increase in the precision of barrel straightness measurements.

Metrics 3 through 5 were met in the second year of the program, as shown in Figure 1. After completion of the firing tests and analysis of the data, it was possible to state that metric 1 was substantially, but not completely, met, while metric 2 was fully met.

The lesson learned: plan, to the extent possible, to acquire and publicize intermediate test results that are indicative of the final performance norm.

Although essentially all the metrics were met, the program did not complete—on time—all of the objectives planned at the outset (Figure 3). Part of this shortcoming could be attributed to good, but not accurate, planning, in that the scheduled second-year design team goal of investigating alternative ways to optimizing the reshaping process did, indeed, find a significant process improvement, which then required time to incorporate. However, because BRI was such a resounding success, ARL offered to fund the cost of completing the machine construction TRL level 9 (TRL 9—the

concept is thoroughly understood and characterized, and integration issues have been addressed—is ready for fielding) by the end of the fifth year, as noted on the timetable of Figure 1.

ASSURING IMPLEMENTATION

As expected, leadership changed at both PM TMAS and PM Abrams during the course of the four-year MTO. In fact, it was not merely leadership change, but both PMs ceased to exist before the end of the program. The roles of PM TMAS were taken over by PM MAS; similarly, PM Abrams was consolidated into PM Combat Systems (CS). Obviously, the new PMs at both organizations needed to be apprised of what the MTO was about, and they needed to take a fresh look at the questions: Why should BRI be implemented, Is it affordable? Because the business team had anticipated such questions as a likely prerequisite to implementation, and because the numerous interim progress reports had, in response to a wide range of technical inquiries, generated an abundance of vantage points from which to view BRI, the program was well prepared with answers to such questions.

With regard to the question of affordability, the business team commissioned a comprehensive cost estimate from Rock Island Arsenal for implementing BRI on all existing tanks. Their analysis showed that the estimated implementation cost per tank is less than the cost of one tactical round of ammunition. But the most compelling reason to implement BRI was the outstanding performance improvement it offered. PM Combat Systems was quoted as saying, "This is the kind of quantum leap forward we're looking for." Presently, BRI is scheduled to begin implementation at the end of year five on the time scale of Figure 1.

SUMMARY

The BRI was a ManTech-funded program with a manufacturing technology objective to develop machinery capable of shaping, or reshaping, tank gun barrel centerlines to a much tighter profile consistency. Its payoff was enhancing the accuracy, and hence the performance, of the fleet-average barrel. Although the MTO was a four-year program, it took eight years to bring the fundamental concept of BRI from the point of discovery and demonstration by Army scientists, to Army acceptance for implementation. The program's acceptance and implementation were ultimately based on the demonstrated performance benefits that would be achieved by the reshaping process. The best practices discovered and lessons learned are summarized in *italics* below.

The concept originated as a result of exploratory research in an area no longer synchronized with a mainstream mission or customer program. The lesson for laboratory managers: *New programs can arise in old areas with new technologies, provided scientists and engineers are given the latitude and encouragement to explore such possibilities.*

After successfully demonstrating the concept, the scientists proceeded to *inform management of the performance benefits* to be gained and solicit their help in finding a funding source to pursue further development. Laboratory *management* recognized the merit of the research and *strengthened the planned proposal by forming an inter-laboratory partnership.* With a

joint laboratory voice, *the proposal was brought to the attention of Army weapon system program managers (PMs).* Although this approach did not lead directly to developmental funding, *it exposed the proposed performance payoff to leadership levels* in the gun community *and netted the pivotal suggestion for the most appropriate funding source*—the ManTech program.

It was highly effective to individually brief the proposal review board prior to the final selection committee meeting, accompanied by a representative from the Training and Doctrine Command (TRADOC) Systems Manager's (TSM) office, to ensure a full appreciation of the proposed benefits from the scientist's and soldier's point of view.

Of course, periodic team and project reviews were essential, but there was an unexpected bonus in holding numerous external reviews before gun-knowledgeable audiences who were seeing the program outlined for the first time.

Breaking down the MTO into teams, each with a common purpose, was the most natural way to address the program goals and objectives, but *having the resources and capacity to handpick the best individuals from multiple organizations to lead and serve on teams was critical to the program's resounding success.*

Of course, periodic team and project reviews were essential, but there was an unexpected bonus in holding numerous external reviews before gun-knowledgeable audiences who were seeing the program outlined for the first time. *External exposure invited challenges to the program's precepts. Responding to these challenges either reinforced or redirected the program approach. In either case, the final product was strengthened.*

Hundreds of items were procured during the four-year BRI program. All purchases were reviewed and approved by the MTO manager. For expediency's sake, however, *it was an extremely valuable practice that the laboratory granted the MTO manager the authority to authorize program-related purchases and supplied the program with the budgeting personnel to quickly process purchase order requests.*

Proper test planning should be done to ensure that the intermediate reporting of partially completed testing will be representative of the final test results, thereby avoiding inaccurate performance projections and misleading generalizations.

James Garner serves as an aerospace engineer for the Army Research Laboratory's Aerodynamics Branch. His duties include aeroballistic evaluation of experimental and developmental ammunition. Garner also serves as an investigator to find methods to alleviate problems in launch and flight dynamics. As such, he is tasked to find novel engineering solutions and manage implementation of new technologies. Garner holds an aerospace engineering degree from the University of Maryland.

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